A Debris-Free Plasma Radiation Source for Extreme Ultraviolet Lithography

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In the quest for increased performance, the microelectronics industry has been reducing the size of individual elements, also known as features, on integrated circuits by a factor of two roughly every six years. Smaller feature sizes result in reduced distance and, therefore, reduced transit time between features, allowing the integrated circuits to be driven at higher clock speeds. Also, greater feature density allows for increased functionality, permitting one chip to perform the tasks that previously required several. This year, commercial devices will become available with 0.18-μm features and with 125 million transistors on a single chip.

In the commercial production of integrated circuits, the patterns for the features are imaged onto a silicon wafer by projection photolithographic methods that use visible and ultraviolet light sources with conventional optics. It is anticipated that this technology will reach its limit at a feature size of 0.15 μm. Achieving features smaller than 0.1 μm using a commercially feasible process will demand advances in future lithography techniques such as using extreme ultraviolet (EUV) radiation in conjunction with molybdenum/silicon multilayer reflective optics. These optics have a maximum theoretical reflectivity of 76% at a wavelength of 13 nm, which is more than an order of magnitude smaller than the shortest wavelength used in today's commercial processes. Using 13-nm radiation will allow for the imprinting of features that may ultimately be smaller than 0.05 μm.

Most of the proposed EUV lithography (EUVL) sources involve the interaction of a high-energy-density source (such as a laser, an electron beam, or an arc discharge) with a solid target. Although all of these methods offer efficient production of EUV radiation, debris generated from solid targets has been demonstrated to deteriorate the very expensive, metal, multilayer system optics. From FY94 to FY96, Los Alamos and Northrop Grumman were developing a debris-free EUVL source under a cooperative research and development agreement (CRADA). This source exploits the predicted anomalous energy deposition of a short-pulse electron beam in a preformed plasma. As a result, the plasma is heated and ionized to a charge state in which efficient radiation with a wavelength of 13 nm or less is generated upon recombination. Because solid targets are avoided, the production of debris is avoided as well. The effort at Los Alamos had three distinct phases: experimental verification of the anomalous energy absorption; construction of a short-pulse, high-brightness accelerator; and the final experiments with the accelerator.

Anomalous energy deposition into a preformed target plasma by a relativistic electron bunch is predicted when the temporal duration (bunch length) is less than or equal to the inverse of the plasma frequency of the target plasma. For a bunch this short, the plasma can no longer respond to the individual electrons but instead responds collectively to the bunch. The energy loss is predicted to scale as the square of the effective charge of the bunch. For a bunch with a few nanocoulombs of charge, ~10^{10} electrons, this scaling suggests a considerable enhancement of stopping power over that of individual electrons. The bunch loses energy by driving a large-amplitude electrostatic wave in the target plasma—that is, by generating a plasma wake field. The goal of this work is to drive the wake-field generation process into the nonlinear, wave-breaking regime so that the energy deposited into the plasma wave will efficiently heat and ionize a plasma column that will generate EUV.

Initial experiments to demonstrate anomalous energy absorption are carried out with the accelerator developed for the Los Alamos Free-Electron Laser as the source of the electron bunches. For these experiments, the accelerator is configured to produce 15-ps, 4-nC electron bunches with an energy of 15.5 MeV. The bunches are produced in a manner that accelerates a series of 1–8 bunches with a spacing of 9.2 ns between each bunch (collectively referred to as a macropulse). The macropulse is injected into a 10-cm-long gas cell containing either 0.18 or 0.5 torr of argon. As the first few electron bunches pass through the cell, a weakly ionized (~0.1% ionization) argon plasma column is created by collisional ionization. The plasma frequency, ω_{pe}, increases with increasing plasma electron density, n_e, by the relationship $\omega_{pe} \propto \sqrt{n_e}$. When the inverse of the plasma frequency equals the bunch length, T_b, or, equivalently, when a critical electron-density is reached (that is, when $n_e \cong 3 \times 10^{15}/T_b^2$ cm^{-3}, where T_b is in picoseconds), the plasma responds collectively to the next bunch and slows the bunch, transferring energy to the background plasma electrons. The heated background plasma ionizes the neutral gas. After the macropulse exits the gas cell, the energy of the individual bunches in the macropulse is measured with a time-resolved energy spectrometer. The plasma density along the ionized filament in the cell is measured with a 94-GHz microwave interferometer.

Figure II-6 shows the measured energy for each bunch with and without gas in the cell. The linear drop in energy for each succeeding bunch measured in the vacuum case is an artifact of the acceleration process. The measured bunch energies with gas in the cell show the anticipated results. The collisional losses of the first three bunches are too small to be detectable by our technique. As the ionization increases, the energy loss suddenly increases, peaks at an optimum plasma electron density, and then lessens as the density becomes too high for efficient energy loss for the fixed bunch length. Figure II-7 shows the percentage of energy loss as a function of the plasma electron density. The maximum observed energy loss is 2.2% (for 0.18 torr) and corresponds to an enhancement of 3.4×10^4 over that expected from collisional ionization and radiative losses. Also shown in Fig. II-7 is the result of numerical simulations of the anomalous energy loss. The simulations, which were performed by researchers in XPA with the particle-in-cell plasma simulation code ISIS, show good agreement with the measurements.

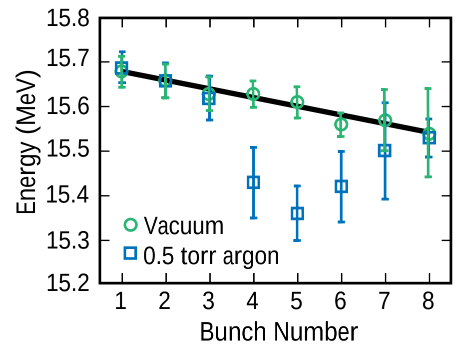

Fig. II-6. Electron energy plotted versus the number of injected electron bunches. The line is a linear fit to the energy of the bunches without a gas fill; the negative slope is an artifact of the acceleration process.

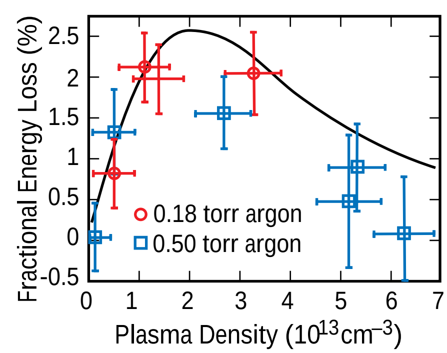

Fig. II-7. Energy loss plotted versus plasma density. The curve is the result from numerical modeling with ISIS.

Although these experiments demonstrate, for the first time, the predicted anomalous energy deposition, the amount of energy deposited is not sufficient to heat and ionize the plasma for EUV production. The fractional energy loss per unit length of a bunch is proportional to the plasma density for a bunch of optimal duration. Numerical calculations show that an 8-MeV, 1.5-nC bunch with a duration of 0.75 ps would suffer an energy loss of 80% for an interaction length of 2.5 mm in a neon plasma with an electron density of ~10^{16} cm^{-3}. Thermalization of the deposited energy results in a 10- to 20-eV plasma filament producing EUV from Ne^{4+} and Ne^{5+} ions. As part of the second phase of the CRADA, a linear accelerator (linac) that can produce bunches with these parameters has been constructed by researchers in AOT-9 (now LANSCE-9). Using photocathode technology, the linac produces 8-MeV-electron bunches with 1.5 nC of charge and an initial length of 20 ps. A time-of-flight compressor, which uses the energy spread created in the acceleration process, reduces the bunch duration to 0.75 ps with no loss of charge. The accelerator can create a macropulse of a series of bunches with a spacing of 9.2 ns. Northrop Grumman developed a pulsed, supersonic gas jet that produces a 0.4-cm $\times$ 1-cm jet of neon with a density of neutral atoms of ~10^{19} cm^{-3}. A photograph of the accelerator is shown in Fig. II-8.

As was seen in the initial experiments, it is anticipated that the first few bunches in the macropulse will create a weakly ionized plasma column in which a trailing pulse will strongly couple and deposit a significant amount of its energy. The configuration of the experiment does not permit time-resolved measurements of the individual bunch energies. The primary diagnostics are two filtered silicon photodiodes that view the interaction region. One diode is coated with layers of titanium, zirconium, and carbon that are 5 nm, 200 nm, and 50 nm

Fig. II-8. The EUVL linac located at Los Alamos. The accelerator generates 8-MeV, 1.5-nC electron bunches that are compressed to a bunch length of 0.75 ps.

thick, respectively. This layering results in a filter that has a band-pass between 6 and 16 nm (200 to 77 eV), which blocks any longer wavelengths and passes radiation shorter than 1.3 nm (950 eV). The second diode has a 127-μm beryllium layer that passes wavelengths shorter than 0.9 nm (1265 eV) and blocks all longer wavelengths. This combination of filters permits the detection of radiation between 6 and 16 nm with the Ti/Zr/C-coated diode while rejecting any signals that may be from x-rays and gamma rays because these signals would be seen in the beryllium-filtered diode.

Figure II-9 shows data from the two diodes. Distinct pulses are evident in the Ti/Zr/C-filtered diode that are absent in the beryllium-filtered diode, indicating the generation of radiation within the 6- to 16-nm band. The first pulse seen in the data is coincident with the fourth bunch of a macropulse that contains 10 bunches. The timing is confirmed by measuring the pulses recorded when a metal target is placed in the interaction region. (Using a metal target results in a gamma-ray pulse for each bunch in the macropulse; this pulse is seen in both detectors.) These results show behavior similar to that seen in the initial experiments. The first few bunches of the macropulse show negligible coupling, after which strong EUV generation occurs for the next few pulses. For these experiments, it can only be assumed that the optimum plasma electron density for this bunch length corresponds to the peak in the EUV generation. (The microwave interferometer used in the initial experiments was not used for these experiments because the plasma electron density is beyond its measurement capabilities.) From the energy absorbed by the photodiode, we estimate that on the order of 1% of the bunch's energy is converted to radiation in this band.

These experiments demonstrate debris-free EUV production using anomalous energy deposition of an electron bunch into a plasma. The technique shows promise as a source for EUVL; however, measurements of the conversion efficiency into the 13-nm (±0.15 nm) band are needed. Northrop Grumman estimates the production cost of a commercial EUV source based on this technology to be $1.5 million, an amount that is comparable to cost estimates of laser-based systems.

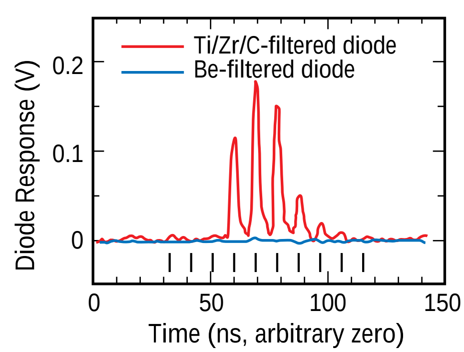

Fig. II-9. Data from the silicon photodiodes that view the interaction region. They indicate the production of EUV in the 6- to 16-nm-wavelength band. The black vertical bars mark the time that each of the 10 electron bunches from a macropulse passes through the interaction region. The data are for a single macropulse.